

Probing the hadron-quark mixed phase at high isospin and baryon density

Sensitive observables

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We like to dedicate this work to the memory of Prof. Liu Bo, of the Institute for High Energy Physics (IHEP) of Beijing, suddenly passed away few months ago, for his continuous interest in the project and for the important contributions.

Abstract. We discuss the isospin effect on the possible phase transition from hadronic to quark matter at high baryon density and finite temperatures. The two-Equation of State (Two-EoS) model is adopted to describe the hadron-quark phase transition in dense matter formed in heavy-ion collisions. For the hadron sector we use Relativistic Mean Field (RMF) effective models, already tested on heavy ion collision (HIC). For the quark phase we consider various effective models, the MIT-Bag static picture, the Nambu–Jona-Lasinio (NJL) approach with chiral dynamics and finally the NJL coupled to the Polyakov-loop field (PNJL), which includes both chiral and (de)confinement dynamics. The idea is to extract mixed phase properties which appear robust with respect to the model differences. In particular we focus on the phase transitions of isospin asymmetric matter, with two main results: i) an earlier transition to a mixed hadron-quark phase, at lower baryon density/chemical potential with respect to symmetric matter; ii) an "Isospin Distillation" to the quark component of the mixed phase, with predicted effects on the final hadron production. Possible observation signals are suggested to probe in heavy-ion collision experiments at intermediate energies, in the range of the NICA program.

1 Motivations

In heavy ion collisions at intermediate beam energies in the AGeV range, rather high density regions can be reached, opening the possibility for new degrees of freedom to come into play. This kind of collisions is usually described for hadronic matter within relativistic mean-field (RMF) models and transport theories [1]. Here we want to show that in neutron-rich systems the transition from the nuclear (hadron) to the quark deconfined (quark-gluon plasma) phase could take place even at density and temperature conditions reached along collision dynamics in the intermediate energy range. Such transition in very isospin asymmetric matter is also of large interest in the study of neutron stars (in the following we in short talk of "asymmetric matter").

Hadronic matter is expected to undergo a phase transition to a deconfined phase of quarks and gluons at large densities and/or high temperatures. On very general grounds,

the critical densities of the transition should be dependent on the isospin of the system, but no experimental tests of this dependence have been performed so far. Moreover, up to now, data on the phase transition have been extracted from ultrarelativistic collisions, when large temperatures but low baryon densities are reached.

In order to check the possibility of observing some precursor signals of new physics even in collisions of stable nuclei at intermediate energies we have performed event simulations for the collision of very heavy, neutron-rich elements. We have chosen the reaction $^{238}\text{U} + ^{238}\text{U}$ (average proton fraction $Z/A = 0.39$) at 1 AGeV and semicentral impact parameter $b = 7 \text{ fm}$ just to increase the neutron excess in the interacting region [2,3]. To evaluate the degree of local equilibration and the corresponding temperature we have followed the momentum distribution in a space cell located in the c.m. of the system; in the same cell we report the maximum density evolution. Results are shown in Fig. 1. We see that after about 10 fm/c a nice local equilibration is achieved. We have a unique Fermi

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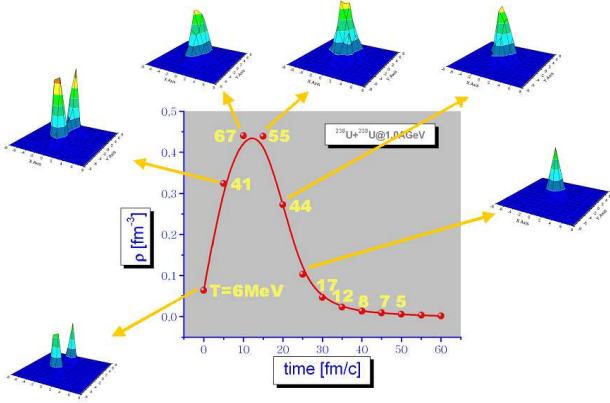


Fig. 1. (Color on line) Uranium-Uranium 1 AGeV semicentral collision. Correlation between density, temperature, momentum thermalization inside a cubic cell 2.5 fm wide, located in the center of mass of the system.

distribution and from a simple fit we can evaluate the local temperature. At this beam energy the maximum density coincides with the thermalization, then the system is quickly cooling while expanding. We can extract the time evolution of all physics parameters inside the c.m. cell in the interaction region. We find that a rather exotic nuclear matter is formed in a transient time of the order of 10 fm/c, with baryon density around 3 – 4 times saturation density ρ_0 , temperature 50 – 60 MeV, energy density 500 MeV fm⁻³ and proton fraction between 0.35 and 0.40, [2,3]. This could be well inside the estimated mixed phase region, as discussed in the following.

1.1 Isospin effect on the Hadron-Quark transition: simple arguments

At high temperature T and small quark chemical potential μ_q lattice-QCD (l-QCD) calculations provide a valuable tool to investigate the transition to the hadronic phase. The transition appears of continuous type (crossover) with a critical temperature T_c around 170-180 MeV. Isospin and other properties of the hadron interaction appear not relevant here [4]. The reason is that at low chemical potential only thermal excitations contribute to the pressure, ruled essentially by the particle degrees of freedom [5].

However the lattice calculations suffer serious problems at large chemical potentials and the validity of the results at $\mu_q/T_c > 1$ is largely uncertain [6]. Some phenomenological effective models have been introduced, like the MIT-Bag [7] and the more sophisticated Nambu-Jona Lasinio (NJL) [8,9] and Polyakov-NJL (PNJL) [10,11,12] models, where the chiral and deconfinement dynamics is accounted for effectively. We remark here that only scalar interactions are generally considered in the quark sector. In the PNJL case the transition at low- μ is well in agreement with l-QCD results [13], however still important in-

teraction channels of the hadron sector are not included and so the expected transition at high baryon and isospin density cannot be fully trusted.

In order to overcome the problem and to get some predictions about the effect of the transition in compact stars [14,15,16,17,18,19] and high energy heavy ion collisions [2,3,4,20,21,22,23,24], recently Two-EoS (Two-Equation of State) models have been introduced where both hadron and quark degrees of freedom are considered, with particular attention to the transition in asymmetric matter.

In this report the discussion is limited to nucleonic hadron matter and u, d quark matter, also consistently with the analysis of intermediate energy collisions, but including the possibility of an extension to strange particles at higher excitation energies [24].

In isospin asymmetric fermionic systems we have a repulsive symmetry term coming from two contributions: kinetic, from the Fermi motion and potential, from the particle interaction (isovector terms). In the nucleonic phase we have both contributions, with the potential one rather important at high densities [25]. At variance, in the quark phase, in all the effective QCD models, we have only the kinetic part, which is rather slowly increasing with the baryon density, being proportional to the Fermi energy [1]. Within this picture we can predict rather relevant isospin effects on the transition in asymmetric matter, which should be seen at the NICA energies:

- i) Onset of the transition at lower densities due to the larger symmetry pressure in the hadron phase;
- ii) Isospin enrichment of the quark component in the mixed phase due to the smaller symmetry repulsion (Isospin Distillation).

Related observables are discussed in final section. Of course the measurements of the NICA project will be important also to shed lights on the relevance of isovector contributions in the quark sector.

2 Mixed phase and isospin distillation

When a mixed (coexistence) phase of quarks and hadrons is considered, the Gibbs conditions (thermal, chemical and mechanical equilibrium)

$$\begin{aligned}\mu_B^H(\rho_B, \rho_3, T) &= \mu_B^Q(\rho_B, \rho_3, T) \\ \mu_3^H(\rho_B, \rho_3, T) &= \mu_3^Q(\rho_B, \rho_3, T) \\ P^H(\rho_B, \rho_3, T) &= P^Q(\rho_B, \rho_3, T),\end{aligned}\quad (1)$$

should be fulfilled [14]. In Eqs. (1), $\rho_B = (1 - \chi)\rho_B^H + \chi\rho_B^Q$ is the mean baryon density and $\rho_3 = (\rho_p - \rho_n) = (1 - \chi)\rho_3^H + \chi\rho_3^Q$ is the isospin density, where χ is the quark fraction. $\rho_B^{H,Q}$ and $\rho_3^{H,Q}$ ($\mu_B^{H,Q}$ and $\mu_3^{H,Q}$) are baryon and isospin densities (chemical potentials), respectively, in the two phases. $P^{H,Q}$ indicates the pressure in the two phases.

The asymmetry parameters for hadronic and quark matter are defined, respectively,

$$\alpha^H \equiv -\frac{\rho_3^H}{\rho_B^H} = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}, \quad \alpha^Q \equiv -\frac{\rho_3^Q}{\rho_B^Q} = 3\frac{\rho_d - \rho_u}{\rho_d + \rho_u}, \quad (2)$$

The factor 3 in the quark case comes from the corresponding baryon and isospin densities $\rho_B^Q = \frac{\rho_d + \rho_u}{3}$, $\rho_3^Q = \rho_u - \rho_d$. For pure neutron matter $\rho_d = 2\rho_u$ and α^Q is consistently 1.

In heavy-ion collisions, for a given isospin asymmetry of the considered experiment, the global asymmetry parameter α

$$\alpha \equiv -\frac{\rho_3}{\rho_B} = -\frac{(1-\chi)\rho_3^H + \chi\rho_3^Q}{(1-\chi)\rho_B^H + \chi\rho_B^Q}, \quad (3)$$

remains constant according to the charge conservation in the strong interaction, but the local asymmetry parameters α^H, α^Q in the separate phases can vary with χ , as determined by the energetically stable state of the system. For details, one can refer to Refs. [21,23,24].

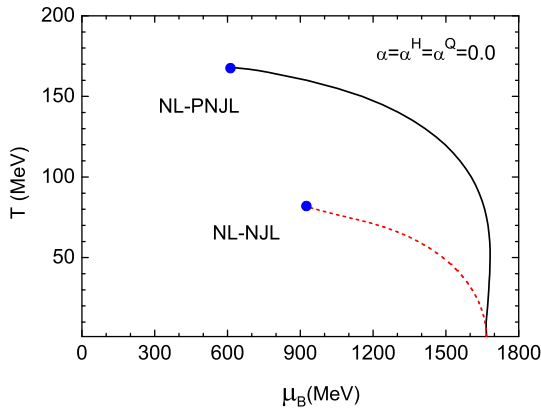


Fig. 2. (Color on line) Phase diagram in $T - \mu_B$ plane for symmetric matter [24].

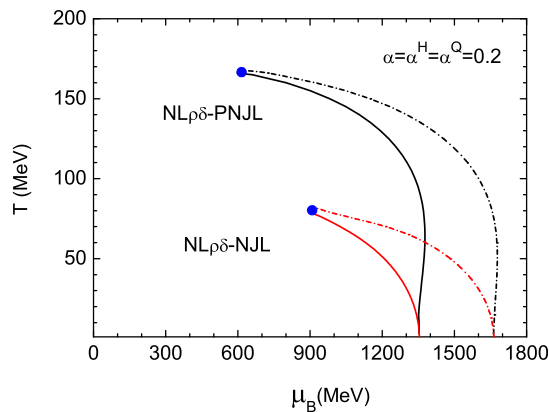


Fig. 3. (Color on line) Phase diagram in $T - \mu_B$ plane for asymmetric matter with the global asymmetry parameter $\alpha = 0.2$, [24]. Full lines $\chi = 0$, dash-dotted lines $\chi = 1$, see text.

In Figs. 2 and 3 we plot the phase transition curves for symmetric and asymmetric matter with the Hadron-NJL and Hadron-PNJL models. In the hadron sector we

use RMF interactions, see the note [25], already tested in heavy ion collisions at lower energies.

At low temperatures a clear earlier onset of the transition is observed for isospin asymmetric matter $\alpha = 0.2$ (see full lines of Fig. 3). In the $T - \rho_B$ plane we see the onset of the transition moving from 6.5 down to 4.5 times the saturation density, [24], as will be seen below in the Fig. 5.

For the NJL model with only chiral dynamics, no physical solution exists when the temperature is higher than ~ 80 MeV. The corresponding temperature is enhanced to about ~ 166 MeV with the Hadron-PNJL model, which is closer to the phase transition (crossover) temperature given by full lattice calculations at zero or small chemical potential. We also note that the expected *Critical - End-Point* in the Hadron-PNJL scheme appears at a quark chemical potential $\mu_q = \mu_B/3 \sim 200$ MeV, just above the critical temperature, which may be accessible in lattice calculations.

Comparing Figs. 2 and 3 we remark that in both NJL and PNJL cases the region around the *Critical - End-Points* is almost not affected by isospin asymmetry contributions, which are relevant at lower temperatures and larger chemical potentials.

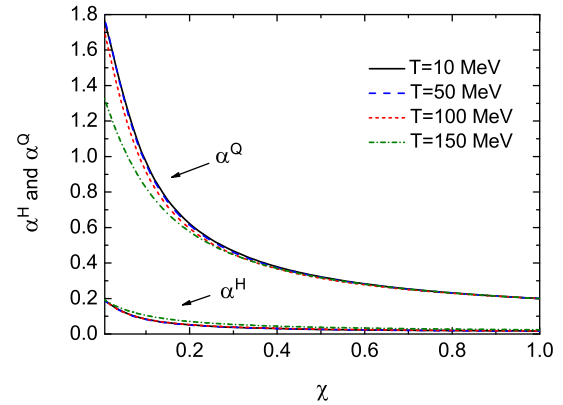


Fig. 4. (Color on line) The behavior of local asymmetric parameters α^H and α^Q inside the mixed phase for several values of temperature. Parameter set $NL\rho\delta$ is used in the calculation [24].

2.1 Isospin Distillation and Isospin Trapping

For symmetric matter there is only one phase-transition line in the $T - \mu_B$ plane, independent of the quark fraction χ . At variance, for asymmetric matter, the phase transition curve varies for different quark fraction χ . The phase transition curves in Fig. 3 are obtained with $\chi = 0$ (solid line) and 1 (dash-dotted line), representing the beginning and the end of the hadron-quark transition, respectively. The reason is that we have an important Isospin Fractionation (Distillation) effect, i.e., an enhancement of the isospin asymmetry in the quark component inside the

mixed phase, as reported in Fig. 4, where the asymmetry parameters in the two components are plotted vs. the quark fraction χ . In asymmetric matter at a fixed temperature, along the transition path, i.e. increasing the quark fraction, pressure and chemical potential change and the two coexisting phases have different asymmetry. The effect is particularly large at the beginning of the mixed phase, i.e. for quark concentrations below 50 %, which is in fact the region expected to be better probed in heavy ion collisions at intermediate energies.

In the hadron phase the neutrons at high density are seeing a large repulsive symmetry term and so are expected to be quickly emitted during the heavy ion collision. At variance, at the onset of the mixed phase the neutrons will be kept in the system since a more isospin asymmetric quark phase should be formed. This is what we call "Isospin Trapping" and we expect observable effects of that in the hadronization during the expansion step, see the final section.

We stress again that the isospin distillation effect is due to the large difference in the symmetry terms in the two phases since all the used quark effective models do not have explicit interaction isovector fields. We have checked that even with isovector terms in the PNJL lagrangian, the effect is still there although a little reduced [26]. In any case the strength of the couplings in the QCD effective lagrangian is completely unknown and also for this reason experiments at NICA appear very relevant.

2.2 Vector quark interactions and existence of hybrid neutron stars

It appears natural to further investigate the role of vector interactions in the quark effective models [26,27]. We remind that in nuclear matter the vector interactions lead to fundamental properties, like the saturation point and the symmetry energy in isospin asymmetric systems. In ref. [26] we have seen how an isovector-vector term in the quark phase can affect the isospin distillation mechanism.

We briefly discuss now some results obtained when the isoscalar-vector interaction channel in the quark sector is turned on in the (P)NJL models. With increasing the ratio $R_V = G_V/G$ of the vector/scalar coupling constants, due to the repulsive contribution of the isoscalar-vector channel to the quark energy and, as a consequence, to the chemical potential, the phase-transition curves are moving towards higher values of density/chemical potential [26, 27].

A larger repulsion in the quark phase is essential for the existence of massive hybrid neutron stars. However a limit appears to be the impossibility of reaching the onset densities of the mixed phase in the inner core for large values of the vector coupling. A massive hybrid neutron star can be supported in the range 0.1-0.3 of the R_V ratio and good agreement with recent data for the Mass-Radius relation is obtained [27]. In this more general respect the NICA data on properties of the mixed phase in Heavy Ion Collisions are of great importance.

3 Conclusion: experimental proposals for the NICA program

Asymmetric matter is interesting for two main reasons: i) Earlier onset of the mixed phase; ii) Isospin distillation to the quark phase. We have seen that noticeable effects can be observed even for relatively low asymmetries, $\alpha \sim 0.2 - 0.3$, thus experiments with stable heavy ions would be sufficient. Of course the availability of very neutron-rich unstable beams in this energy range could be very important.

The best region of the nuclear matter phase diagram to observe the mixed phase appears to be at temperatures $T \sim 50 - 100 \text{ MeV}$, chemical potentials $\mu_B \sim 1200 - 1800 \text{ MeV}$ (densities $\rho \sim 3 - 6\rho_0$). This can be achieved in HIC (fixed target) at beam energies $3 - 10 \text{ AGeV}$, $\sqrt{s_{NN}} \sim 3 - 5 \text{ GeV}$, well inside the reach of the NICA project.

3.1 Suggested Observables

As stressed before, since an equation of state able to describe the two phases is not presently available we cannot present results of a transport simulation of heavy ion collisions with hadron-quark transitions. However from our knowledge of the hadronic collisions and from the results of the Two-EoS model discussed here we can suggest some possible interesting experiments in the NICA energy range. An important general point is to concentrate on particles emitted at high transverse momentum. Indeed this kind of emission essentially occurs during the first stage of the collision, when a significant degree of compression is reached. Thus these particles are expected to keep track of the features of asymmetric high density matter. We can list:

Onset of quark degrees of freedom:

i) In heavy ion collisions at intermediate energies, the high pressure reached in the high density phase induces an anisotropic azimuthal distribution of the emitted particles, with a negative elliptic flow v_2 . The onset of the quark phase would cause an EoS softening, due to the lack of repulsive vector interactions in the quark matter joint to an increase of the degrees of freedom. Then we would expect to observe a less negative v_2 , with respect to theoretical predictions considering only hadronic matter.

ii) Since hadrons may also be produced from the quark phase, one could observe, already at intermediate energies, the onset of n_q -scaling of the flows of the emitted particles, already seen at RHIC-LHC energies [28]. Of course one has to consider that lowering the beam energy the impact of the hadronic rescattering is expected to increase and one should argue that most of the flow is build-up in the early quark phase. Nonetheless the n_q acquires a stronger significance at higher momenta ($> 1 \text{ GeV}$) that are associated to the early stage dynamics and are marginally affected by the later rescattering. A quantitative study is certainly necessary in this direction.

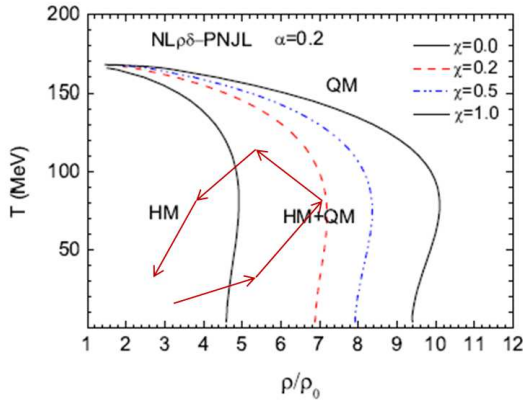


Fig. 5. (Color on line) Phase diagram in $T - \rho_B$ plane in the Two-EoS model for asymmetric matter with the global asymmetry parameter $\alpha = 0.2$. χ represents the fraction of quark matter.

Isospin Distillation, d -rich quark phase. At the NICA beam energies we can figure out a compression-expansion path inside the mixed phase like the one shown in the Fig. 5 (the arrow line, just pictorial representation). We can expect a remaining influence on the final hadron formation, according to the following considerations:

i) The isotopic content of light cluster emission is seen to increase with the beam energy, owing to the higher compression reached and to the more repulsive isovector interaction [29]. However, if quark matter starts to co-exist with hadronic matter, the latter becomes more symmetric. Then one should observe a sudden inversion in the trend of emission of fast neutron-rich clusters with increasing beam energy, to be probed looking at the n/p , $^3H/^3He$... ratios at high transverse kinetic energy.

ii) Correspondingly, one should observe an enhanced production of isospin-rich nucleon resonances (and subsequent decays), originating from the quark phase.

iii) Related to the previous point, one would expect an anomalous increase of π^-/π^+ , K^0/K^+ yield ratios for mesons coming from high density regions, i.e. with high transverse momentum p_T . We note that in absence of the phase transition, these ratios would keep smaller due to the fast neutron emission, as mentioned above, which inhibits the production of d -rich mesons in inelastic nucleon-nucleon collisions.

All these effects will be more relevant in the lower energy part of the mixed phase, where the isospin distillation appears larger. A Beam Energy Scan procedure would be appropriate for the suggested isospin observables in the beam energy range 3 – 10 AGeV. Recently a similar beam energy search for the mixed phase in Heavy Ion Collisions has been suggested for other observables, like transverse mass, rapidity distribution and strangeness production [30]. We propose here an extension to isospin anomalies using colliding ions with large charge asymmetries.

Finally the NICA results will be important for tuning the vector interactions in the quark sector, relevant for neutron star models and in general for the development of a unified effective field theory of the two phases.

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